

THE ATMOSPHERE EXPLORER AND THE SHUTTLE GLOW

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Abstract. Recent analyses of the Atmosphere Explorer data are discussed in which it is demonstrated that the satellite glows have two components, one at high altitudes which is consistent with excitation in single collisions of atmospheric oxygen atoms with the vehicle surface and the other at low altitudes which is consistent with double collisions of nitrogen molecules. Contrary to an earlier suggestion, the low-altitude data are not consistent with single collisions of oxygen molecules.

The separation of the two components strengthens the conclusion that the high-altitude glow arises from vibrationally excited OH molecules produced by a formation mechanism that is different from that leading to the normal atmospheric OH airglow. The spectrum is consistent with association of oxygen and hydrogen atoms at sites on the surface into the vibrational levels of OH. The low-altitude glow is consistent with the Green mechanism but there are difficulties with it.

The shuttle glows are different and have the spectral appearance of emission from NO₂. The characteristics of the shuttle glows and the satellite glows will be contrasted and a tentative resolution of the differences in the Atmosphere Explorer and shuttle glows will be offered.

Discussion

Much detailed information about the glows resulting from the interaction of spacecraft with the atmospheric environment has been acquired from studies of the data provided by the Visible Airglow Experiment onboard the Atmosphere Explorer satellites [Hays et al., 1973]. Figure 1 illustrates the glow intensity at 732 nm as a function of altitude [Yee and Abreu 1982, 1983]. Above 160 km the intensity is directly proportional to the ambient number density [O] of atomic oxygen. Yee and Abreu [1982, 1983] suggested that the glow was produced by oxygen-containing metastable molecules released from the surface after energetic collisions with oxygen atoms and they drew attention to laboratory studies of OH, NO and NO₂ surface luminosities. The shuttle glow intensity appears to increase with diminishing altitude and may also be proportional to [O] [Banks et al., 1983; Mende et al., 1983, 1984a,b, 1985].

Yee and Abreu [1982, 1983] analyzed the variation of the glow intensity with the angle of attack and obtained a distribution $\cos^3\phi$ with some emission persisting to an angle of 120°. In laboratory studies of the dissociative absorption probability, the variation with ϕ depends upon the interacting species and the nature of the surface. A variation as $\cos^3\phi$ happens to be consistent with a one-dimensional barrier model of desorption which has received experimental support from studies of the interaction of the light molecule H₂ with Cu surfaces

[Balooch et al., 1974]. For the heavier molecule N_2 on a W(110) surface, in contrast, the dissociative absorption probability depends only weakly on angle [Auerbach et al., 1984] as apparently does the shuttle glow intensity [Mende et al., 1984a,b].

The efficiency with which the glow is produced on the AE satellites for each collision of an oxygen atom was found to increase during the satellite lifetimes indicating that surface processing was occurring [Yee et al., 1984]. The shuttle does not remain in orbit long enough for time-dependent effects on the luminosity to be detectable though direct shuttle-based measurements have demonstrated a substantial erosion of various materials and the glow intensity depends upon the surface material [Mende et al., 1984b, 1985].

The observation of a glow at angles greater than 90° on the AE satellites was attributed to the surface release of excited molecules with a finite radiative lifetime [Yee and Abreu, 1982, 1983]. The distribution with ϕ is consistent with a decay length of 10 m. Because the analysis did not take account of the Maxwellian velocity distribution of the impacting atoms, the derived value of 10 m should be regarded strictly as an upper limit. The corresponding radiative lifetime probably lies between 10 ms and 1 ms.

The shuttle glow can be analyzed more directly in that the glow is seen to be spatially extended. A careful analysis of the photographs of the glow yielded a decay length of 20 cm and suggested that the mechanisms of the AE and shuttle glows are different [Yee and Dalgarno, 1983, 1985].

The measured intensity ratio of the AE glow in the band passes centered at 732 nm and 656 nm is 2.15 between 170 and 175 km and 2.25 between 140 and 145 km [Yee and Abreu, 1982, 1983; Langhoff et al., 1983], close to the OH intensity ratio observed in the night airglow. Together with the inferred radiative lifetime, the similarity of the intensity ratios led Slanger [1983] to suggest vibrationally-excited OH as the molecule responsible for the AE luminosity. Further data obtained over a wavelength range extending to 280 nm [Yee and Abreu, 1983] gave a spectrum which differs from that of the airglow but Langhoff et al. [1983] showed that the OH identification could be retained by postulating OH formation through a surface association mechanism that populates all the vibrational levels at nearly uniform rate. Their model reproduced satisfactorily the shorter wavelength data but it yielded a 732 nm/656 nm intensity ratio between 5.6 and 7.4. They suggested tentatively that the discrepancy with the measured ratio of 2.15 was due to the uncertainties in the line positions of transitions originating in the high vibrational levels for which no laboratory data exist.

Additional support for the OH identification was obtained from measurements with a Fabry-Perot interferometer onboard the Dynamics Explorer DE-B satellite [Abreu et al., 1985]. Two lines were detected whose positions, corrected for the Doppler shift arising from the moving satellite, coincide with lines of OH. A third line was detected which could also be due to OH. Although persuasive, we note that the lines also coincide in position within the accuracy of the measurements with three lines of the first positive system of N_2 .

The spectrum of the shuttle glow [Mende et al., 1983, 1984a,b 1985] is different from the AE glow. It appears to be without structure and is very similar to the NO_2 recombination continuum [Swenson et al.,

1985]. Emission from NO_2 has been the subject of many laboratory studies [Fontijn et al., 1964; Paulsen et al., 1970; Kenner and Ogryzlo, 1984; Kuwabara et al., 1984]. Swenson et al. [1985] suggested that NO, produced by the ramming N_2 and O, remains on the surface where it reacts further with the ambient oxygen atoms. A more efficient mechanism may utilize the ambient NO molecules and N atoms and N_2O may be formed as well as NO_2 . The excited NO_2 molecules have a lifetime of about 80 μs at 500 nm [Schwartz and Johnston, 1969]. To be consistent with the derived spatial extent of 20 cm [Yee and Dalgarno, 1983], the NO_2 must be released with a velocity of 2.5 km s^{-1} corresponding to a kinetic energy of about 1.4 eV.

An alternative theory of the spacecraft glow has been advanced by Papadopoulos [1984]. According to it, energetic electrons are produced by a plasma interaction and the glow is caused by electron impact excitation. The plasma phenomenon determines the spatial extent of the glow. We have extended an earlier study by Kofsky [1984] of the expected spectrum. As Kofsky [1984] pointed out, the most intense emissions appear in the ultraviolet, a region not yet observed on the space shuttle. Weaker emissions occur in the visible and infrared but the behavior of the spectrum below 600 nm is quite different from both the shuttle and the AE spectra.

The plasma mechanism leads to a glow intensity which increases with the ambient electron density. The AE glow has been analyzed. No correlation was found between its intensity and the electron density [Yee et al., 1984].

Below 160 km, the intensity of the AE glow is no longer proportional to $[\text{O}]$ and the spectrum is different [Yee and Abreu, 1982, 1983]. Slanger [1983] remarked that the enhancement in the glow intensity above that obtained by extrapolating the contribution from atomic oxygen was directly proportional to the number density $[\text{O}_2]$ of ambient molecular oxygen, but a more detailed study by Yee et al. [1985] of a larger data base concludes instead that the glow intensity can be represented by the expression

$$I_\lambda = k_o(\lambda)[\text{O}] + k_{\text{N}_2}(\lambda)[\text{N}_2]^2 \quad (1)$$

where $[\text{N}_2]$ is the number density of ambient molecular nitrogen. The variation as the square of $[\text{N}_2]$ could be alternatively a variation as the product of any pair of the molecules N_2 , O_2 and NO which have similar scale heights in the altitude range of the observations. A variation as $[\text{N}_2]^2$ indicates a mechanism involving the successive collisions of two molecules and is consistent with the mechanism suggested by Green [1984] for the shuttle glow. However if it is to make a significant contribution to the shuttle glow, its efficiency must be several orders of magnitude greater on the shuttle than the values derived for the AE satellites. A possible objection to the Green mechanism is the success of the ion mass spectrometric measurements of atomic nitrogen [Engbreton and Mauersberger, 1979] on the AE satellites which argues that little dissociation of N_2 occurred. If N_2 is not dissociated by impact with the surface, the shuttle glow mechanism may be modified by invoking ambient N or NO in place of the dissociated N_2 .

Table 1, reproduced from Yee et al. [1985], gives the derived relative intensities from the process involving O and from the process

involving N_2 . The N_2 mechanism gives rise to a spectrum decreasing rapidly in intensity at the shorter wavelengths, and its increasing importance at low altitudes is responsible for the steeper glow spectrum below 160 km. At longer wavelengths, the spectrum bears some similarity to the spectrum measured on the Spacelab 1/shuttle mission degraded to match the resolution of the AE photometer [Torr and Torr, 1985]. The spectrum resulting from the Green mechanism is not available and it is unclear how well it might reproduce the observations.

The discrepancy between the model value of the 732 nm/656 nm intensity ratio and the value corresponding to the oxygen mechanism, shown in Table 1, is substantial. It can be removed by postulating an additional source of emission in the spectral region between 600 and 700 nm. A plausible candidate is the shuttle glow mechanism.

A microdensitometer trace of the objective grating spectrum of the glow on the tail of the shuttle STS-8 gave an intensity per unit wavelength near 700 nm of about 450 R/Å corresponding to a total glow intensity of 1MR [Mende et al., 1984a]. The shuttle glow intensity is enhanced by the oblique geometry of the observations. Corrected to a direction normal to the shuttle surface, we estimate an intensity between 10 and 20 R/Å. For the AE satellite the intensity is reduced further by the curvature of the satellite surface to between 5 and 10 R/Å corresponding to a total of 150 R if the shuttle mechanism is operating on the AE satellite. The baffle of the AE airglow photometer extrudes 8 cm above the surface, and bearing in mind the short decay length of the shuttle glow, we estimate that of the total 150 R only 30 R would be detected. The total measured intensity is 60 R and we suggest that half the measured high-altitude glow on the AE surfaces arises from the mechanism that has been attributed to OH and half from the shuttle mechanism that has been attributed to NO_2 . Table 2 compares the resultant relative intensities with those measured above 160 km. The agreement is close. A more quantitative study is in progress.

We believe the OH mechanism also operates on the shuttle but is weak compared to the NO_2 mechanism in the visible. It may be detectable between 1 and 2μ if the calculations of Langhoff et al. [1983] are appropriate.

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References

- Abreu, V. J., W. R. Skinner, P. B. Hays, and J-H. Yee, Optical effects of spacecraft-environment interactions: Spectrometric observations by DE-B satellite, J. Spacecraft and Rockets, **22**, 177-180, 1985.
- Auerbach, D. J., H. E. Pfnur, C. T. Rettner, J. E. Schlaegel, J. Lee, and R. J. Madix, Kinetic energy and angular dependence of activated dissociative absorption of N_2 on W(110): Observed insensitivity to incidence angle, J. Chem. Phys., **81**, 2515-2516, 1984.

- Balooch, M., M. J. Cardillo, D. R. Miller, and R. E. Stickney, Molecular beam study of the apparent activation barrier association with the absorption and desorption of H on Copper, Surf. Sci., 46, 358-392, 1974.
- Banks, P. M., P. R. Williamson, and W. J. Raitt, Space Shuttle glow observation, Geophys. Res. Lett., 10, 118-121, 1983.
- Engebretson, M. J., and K. Mauersberger, The impact of gas-surface interactions on mass spectrometric measurements of atomic nitrogen, J. Geophys. Res., 84, 839-844, 1979.
- Fontijn, A., C. B. Meyer, and H. I. Schiff, Absolute quantum yield measurements of the NO-O reaction and its use as a standard for chemiluminescent reactions, J. Chem. Phys., 40, 64-70, 1964.
- Green, B. D., Atomic recombination into excited molecular nitrogen-A possible mechanism for Shuttle glow, Geophys. Res. Lett., 11, 576-579, 1984.
- Hays, P. B., G. Carignan, B. C. Kennedy, G. G. Shepherd, and J. C. G. Walker, The Visible-Airglow Experiment on Atmospheric Explorer, Radio Science, 8, 369-377, 1973.
- Kenner, R. D., and A. E. G. Ogryzlo, Orange chemiluminescence from NO₂, J. Chem. Phys., 80, 1-6, 1984.
- Kofsky, I. L., Spectroscopic consequences of Papadopoulos' discharge model of spacecraft ram glows, Radio Science, 19, 578-586, 1984.
- Kuwabara, S., K. Kuwata, I. Nishiyama, and I. Hanazaki, Acoustically oscillating emission from NO₂* produced by infrared photosensitized reaction in SF₆+NO₂, Chem. Phys. Lett., 106, 540-543, 1984.
- Langhoff, S. R., R. L. Jaffe, J-H. Yee, and A. Dalgarno, The surface glow of the Atmosphere Explorer C and E satellites, Geophys. Res. Lett., 10, 896-899, 1983.
- Mende, S. B., O. K. Garriott, and P. M. Banks, Observations of optical emissions on STS-4, Geophys. Res. Lett., 10, 122-125, 1983.
- Mende, S. G., P. M. Banks, and D. A. Klingelsmith, Observation of orbiting vehicle induced luminosities on the STS-8 mission, Geophys. Res. Lett., 11, 527-530, 1984a.
- Mende, S. B., G. R. Swenson, and K. S. Clifton, Preliminary results of the Atmospheric Emissions Photometric Imaging Experiment (AEPI) on Spacelab 1, Science, 225, 191-193, 1984b.
- Mende, S. B., G. R. Swenson, K. S. Clifton, R. Gause, L. Leger, and O. K. Garriott, Space vehicle glow measurements on STS 41-D, J. Spacecraft and Rockets, submitted, 1985.
- Papadopoulos, D., On the Shuttle glow (the plasma alternative), Radio Science, 19, 571-577, 1984.
- Paulsen, D. E., W. F. Sheridan, and R. E. Huffman, Thermal and recombination emission of NO₂, J. Chem. Phys., 53, 647-658, 1970.
- Schwartz, S. E., and H. S. Johnston, Kinetics of nitrogen dioxide fluorescence, J. Chem. Phys., 51, 1286-1302, 1969.
- Slanger, T. G., Conjectures on the origin of the surface glow of space vehicles, Geophys. Res. Lett., 10, 103-132, 1983.
- Swenson, G. R., S. B. Mende, and K. S. Clifton, Ram vehicle glow spectrum: Implication of NO₂ recombination continuum, Geophys. Res. Lett., 12, 97-100, 1985.
- Torr, M., and D. G. Torr, A preliminary spectroscopic assessment of the Spacelab 1/Shuttle optical environment, J. Geophys. Res., 90, 1683-1690, 1985.

- Yee, J-H., and V. J. Abreu, Optical contamination on the Atmospheric Explorer-E Satellite, SPIE Proceedings, 338, 120-129, 1982.
- Yee, J-H., and V. J. Abreu, Visible glow induced by spacecraft-environment interaction, Geophys. Res. Lett., 10, 126-129, 1983.
- Yee, J-H., and A. Dalgarno, Paper AIAA-03-2660-OP, Radiative lifetime analysis of the Shuttle optical glow, Environment and Operations Meeting, 191-197, 1983.
- Yee, J-H., and A. Dalgarno, Radiative lifetime analysis of the Shuttle optical glow, J. Spacecraft and Rockets, submitted, 1985.
- Yee, J-H., V. J. Abreu, and A. Dalgarno, Characteristics of the spacecraft optical glow, Geophys. Res. Lett., 11, 1192-1194, 1984.
- Yee, J-H., V. J. Abreu, and A. Dalgarno, The Atmosphere Explorer optical glow near perigee altitudes, Geophys. Res. Lett., submitted, 1985.

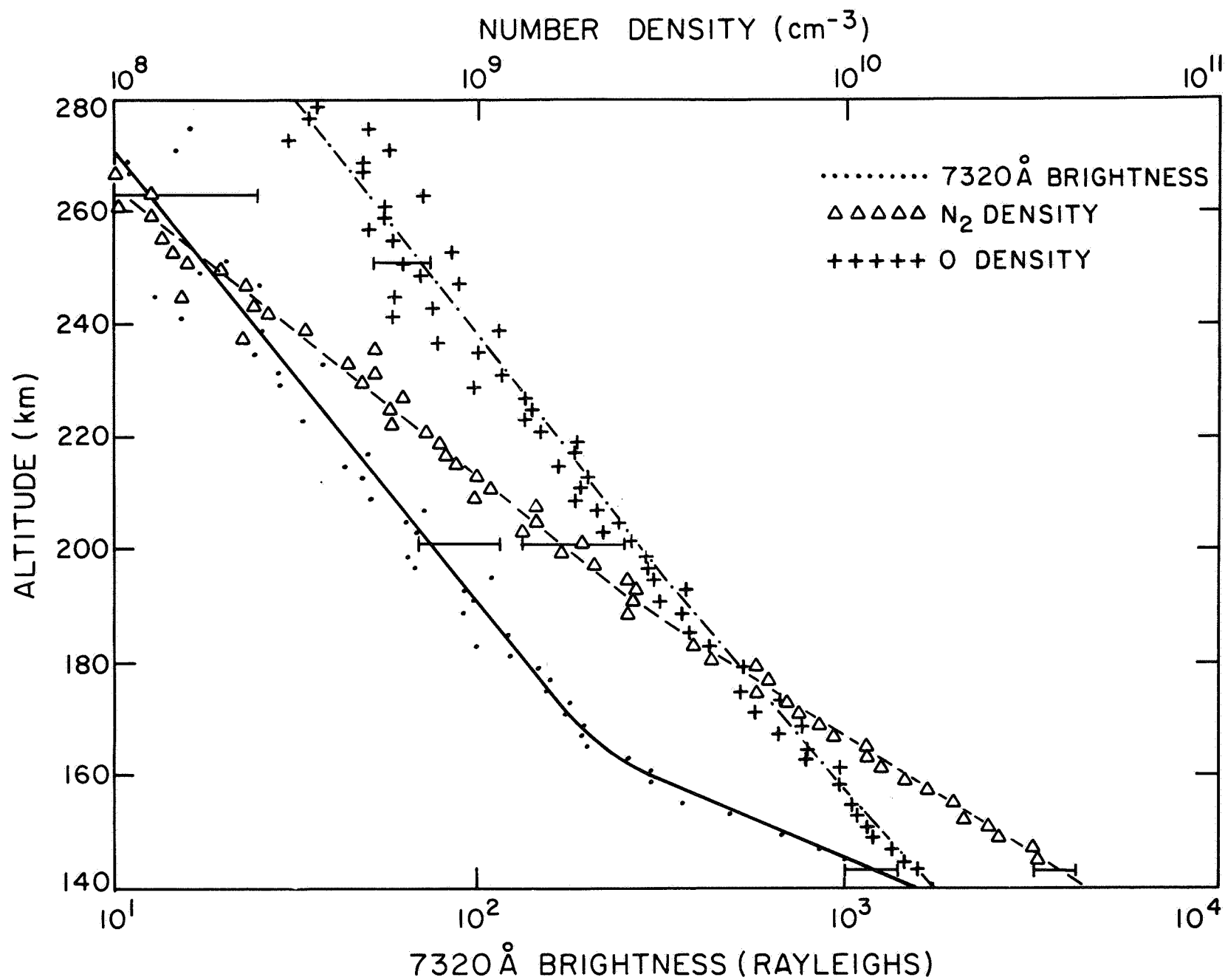


Fig. 1. The Atmosphere Explorer glow at 732 nm in Rayleighs as a function of altitude.

TABLE 1. INTENSITY RATIOS^{*}

(nm)	Theoretical	Empirical			
	O-H recombination	O-mechanism		N ₂ -mechanism	
		(i)	(ii)	(i)	(ii)
732	1.00	1.00	1.00	1.00	1.00
656	0.18-0.13	0.71	0.68	0.09	0.08
428	0.05-0.03	0.02	0.02	0.06	0.06
337	0.06-0.02	0.05	0.04	0.21	0.17
280	---	0.08	0.03	0.19	0.08

* (i) $k(\lambda)/k(732)$ (ii) $\frac{k(\lambda)}{\Delta(\lambda)} \frac{\lambda(732)}{\Delta(732)}$

TABLE 2. AE GLOW SPECTRUM

	OH [*]	NO ₂	I _{OH} +I _{NO₂}	K _O
	(Langhoff et al., 1983)	(Swenson et al., 1985)		(Yee et al., 1985)
7320 Å	1.000	1.00	1.000	1.000
6563 Å	0.159	1.00	0.580	0.679
4278 Å	0.030	0.05	0.040	0.021
3371 Å	0.022	-	0.012	0.036